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# Large-scale wind generation simulations: From the analysis of current installations to modelling the future

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**Abstract.** Modelling and understanding variability in wind generation will be increasingly important in the future with growing shares of wind power in energy systems. Crucially, the modelling needs to be extended to future scenarios, also considering the expected technological development of installations. Reanalysis data is often used in large-scale simulations to model the variability in wind. Wind power plant (WPP) data is also required, but may be only partially available. In this paper, a methodology for estimating missing hub height data is presented, using multiple regression models and large WPP and turbine datasets. The resulting estimated hub heights are presented on a pan-European level, and a scenario with capacity factor development until 2050 for two example countries is shown in detail.

## 1. Introduction

As the amount of installed wind power increases, there is a growing need to model variability in wind generation in detail. As the degree of interconnection in Europe has grown significantly, the modelling of wind generation variability needs to be seen as a pan-European, rather than a country-specific issue. In addition to considering current installations, the modelling needs to be extended to future scenarios with changing wind power technologies. Such modelling is needed for databases such as the ENTSO-E's Pan-European Climate Database (PECD) which is used for electricity market and network studies.

There exists a large amount of literature on the use of meteorological reanalysis data in wind generation simulations, e.g., [1]-[4]. To take into account the differences between mesoscale modelling output and the local wind speeds wind power plants (WPPs) experience, scaling of the reanalysis wind speeds is often required [1], [2].

To apply reanalysis wind speeds in wind generation simulations, information about WPP installations is needed. In the dataset used in this paper, many of the technical parameters of the WPPs are missing. More than half of the installed onshore wind generation capacity has missing hub height information. As hub height is a crucial parameter when applying reanalysis data, a methodology for estimating the missing hub heights was created.

This paper shows the resulting estimated hub heights on a pan-European level, with focus on the differences between regions. Results for two countries with different existing WPP installations, namely Denmark and Finland, are presented in detail. The importance of estimating the missing hub height data when applying the reanalysis wind speed scaling is demonstrated. In addition, the different expected future capacity factor (CF) developments for these two countries are presented.



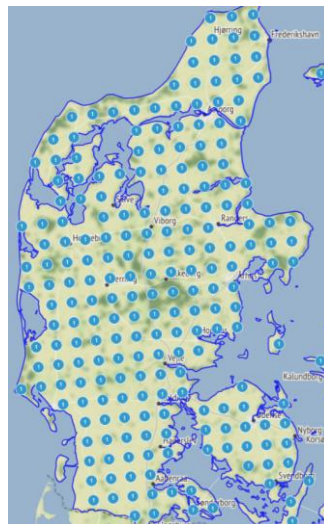
## 2. Reanalysis data in wind generation simulation

This section presents the meteorological reanalysis data used in this study. Scaling, which is used to calibrate the simulated wind speed time series to meet historical CF data, is also described. The modelling is carried out using the CorRES tool developed at the Technical University of Denmark, Department of Wind Energy [5].

### 2.1. The meteorological reanalysis data

The simulated wind generation time series used in this paper are based on reanalysis data obtained from the Weather Research and Forecasting (WRF) model, which is a mesoscale modelling system [6]. To generate the meteorological time series of interest, most importantly wind speeds, the downscaling presented in [7], [8] has been used.

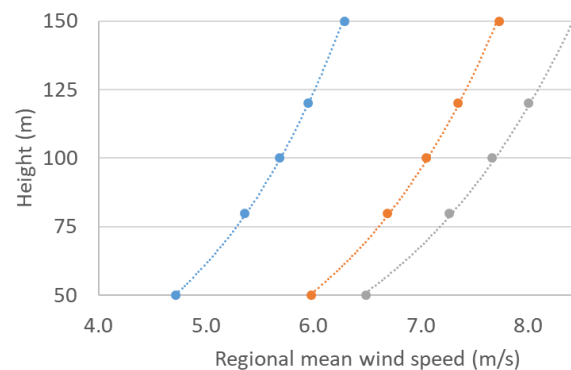
The WRF model gives hourly meteorological time series on a 10 km x 10 km grid, as shown for an example geographical area in Figure 1. Covering the area under modelling, the grid of data can be used to simulate what wind generation output would be with a given set of installations with given technical WPP parameters. The capabilities of the approach for modelling important spatiotemporal dependencies in wind generation have been demonstrated, e.g., in [3], [4]. 35 years of WRF data were available for simulating the wind generation time series used in this study.



**Figure 1.** The meteorological simulation points used when modelling onshore wind generation in western Denmark.

### 2.2. Using wind speed at hub height

When wind speeds are obtained from the WRF model as explained in the previous subsection, they are given for a specific height. When modelling wind power output, they are retrieved at the representative hub height of the generation location being modelled (if modelled turbines have different hub heights, the mean hub height weighted by installed capacity is used). Especially on lower heights, the mean wind speeds are very different on different hub heights, as can be seen in Figure 2. This emphasizes the importance of having correct hub height data in reanalysis modelling.



**Figure 2.** Mean wind speeds (regional averages) at different hub heights for three example regions with different wind resources.

### 2.3. Scaling of reanalysis wind speeds

Although reanalysis data is very suitable for modelling large-scale wind generation, it has been shown that using reanalysis wind speeds directly can cause errors in estimated CFs [1], [2], [4]. To remedy this, scaling of the reanalysis wind speeds have been proposed in [1], [2]. A scaling similar to [2] is used in this paper. Wind speeds acquired from WRF modelling are scaled until a historical target CF is reached. The historical data are either CFs directly (if available), or CFs calculated from installed capacities and annual energy generation data.

## 3. Estimating today's hub heights

This section starts by describing datasets used in this study. Then, a methodology for estimating the significant amount of missing hub height data is explained by first describing the general procedure, and then explaining the required regression modelling. Finally, the resulting hub heights on European level are presented.

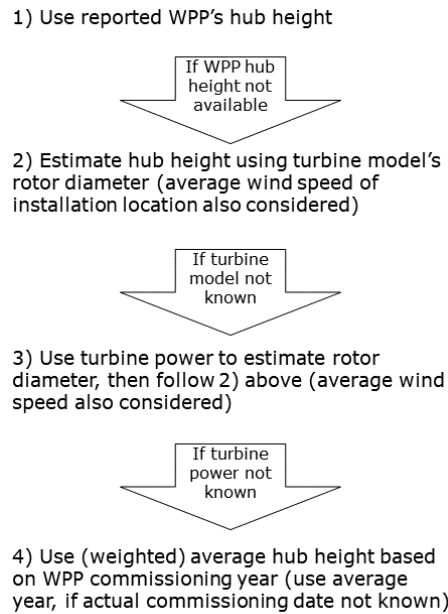
### 3.1. Datasets used

The WPP dataset acquired from [9], with e.g., WPP locations and installed capacities, was used as the basis for the reanalysis simulations. The dataset, and a turbine dataset from the same source, are also used in the estimation of the missing hub heights. Although a majority of the onshore WPPs do not have hub height in the available data, 6090 WPPs with hub height data were still available for the regression modelling needed in the missing data estimation.

### 3.2. Overview of hub height estimation

The hub height estimation procedure consists of several stages, as shown in Figure 3. Stage 1) means simply that if the dataset has a hub height given for a WPP, it is used. If hub height data does not exist, but turbine model is known, the turbine model's rotor diameter is used in regression modelling to estimate the hub height in stage 2). A hub height specified for a turbine type in the turbine dataset is not used, as the ranges of possible hub heights for many turbine types are very wide.

If turbine type is not known, in stage 3) knowledge of turbine rated power is used in the estimation of the WPP hub height. Turbine power can be calculated from the WPP's installed capacity and number of turbines. If even turbine power is not known, commissioning year is used in estimating the hub height in stage 4).



**Figure 3.** The different stages in the hub height estimation procedure. A later stage is reached only if the hub height cannot be estimated in the previous stage. Stage 4) can be carried out for any WPP, so ultimately all WPPs will have a hub height estimate.

### 3.3. Regression modelling

In the hub height estimation procedure shown in Figure 3, regression modelling is needed in both stages 2) and 3). Figure 4 shows the main explanatory variables when estimating hub height in stage 2). Larger rotor diameter clearly indicates a higher hub height, which makes sense as the turbine gets physically larger. However, there is significant variance in hub height with a given rotor diameter, which indicates that additional explanatory variables may be needed.

As can be seen Figure 4, with a given rotor diameter, a location with a lower mean wind speed seems to be associated with a higher hub height. Mean wind speeds were taken from Global Wind Atlas (GWA) [10] using the latitude and longitude of each WPP. In addition, it was noticed that all differences in hub heights between the different countries cannot be explained only by rotor diameter and the location's mean wind speed, so a dummy variable describing the country the WPP is located in was added to the regression model. The final model to be estimated for stage 2) is

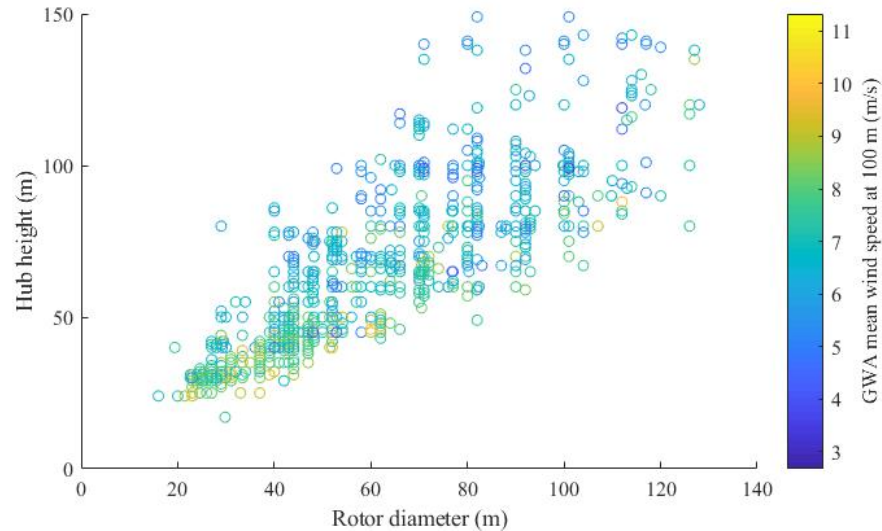
$$y_{hh} = b_0 + b_{dRot}x_{dRot} + b_{ws}x_{ws} + b_{dRot\_ws}x_{dRot}x_{ws} + b_1x_1 \dots + b_kx_k + e, \quad (1)$$

where  $y_{hh}$  is hub height,  $x_{dRot}$  is rotor diameter,  $x_{ws}$  is mean wind speed at the location,  $e$  is the error term of the model and the  $b$  parameters are the coefficient to be estimated. The part  $b_1x_1 \dots + b_kx_k$  of (1) is the dummy variable system signalling the different countries analysed.

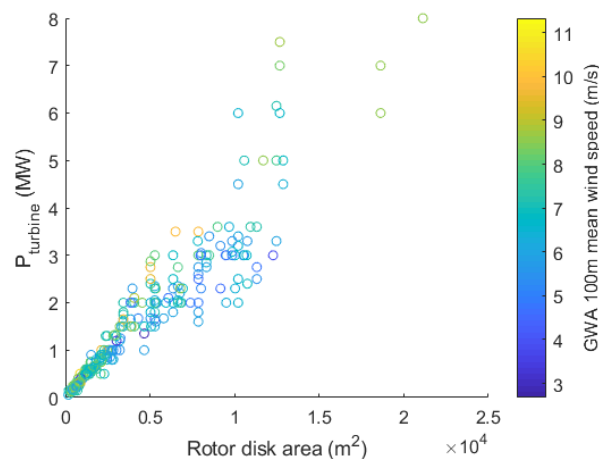
The most important estimated coefficients of (1) are shown in Table 1. It can be seen that an increase in rotor diameter predicts higher hub height, which makes sense. The coefficient for  $x_{ws}$  is zero (it was not found statistically significant in the regression modelling); however, the coefficient for  $x_{dRot}x_{ws}$  is negative. This means that an installation location with a higher mean wind speed predicts a lower hub height for a given rotor diameter, but the magnitude of this effect depends on the diameter. These results are in line with the visual analysis of Figure 4.

For stage 3), the regression model is built based on the dependencies shown in Figure 5. It can be seen that rotor disk area and turbine rated power are highly correlated, which makes sense as a large rotor is usually associated with high rated power. The modelling for stage 3) is built so that turbine rated power can be used to estimate disk area, while also considering the mean wind speed of the installation

location. The estimated disk area is then used to calculate rotor diameter, and the diameter is used in (1) to estimate the hub height.



**Figure 4.** Rotor diameter and hub height of WPPs with colouring using Global Wind Atlas (GWA) average wind speed [10] at installation location.



**Figure 5.** Rotor disk area and turbine rated power with colouring using Global Wind Atlas (GWA) average wind speed [10] at installation location.

**Table 1.** Most important estimated coefficients of (1)

Estimated coefficient	
$b_{dRot}$	1.132
$b_{ws}$	0
$b_{dRot\_ws}$	-0.0509

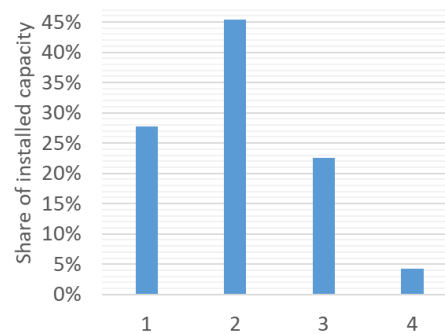
### 3.4. Results on pan-European level

Utilising the missing hub height estimation methodology described in the previous subsections, hub heights were estimated for each WPP in the dataset. Figure 6 shows how the different hub height estimation stages were used in giving a hub height for each WPP. It can be seen that stage 2) was used

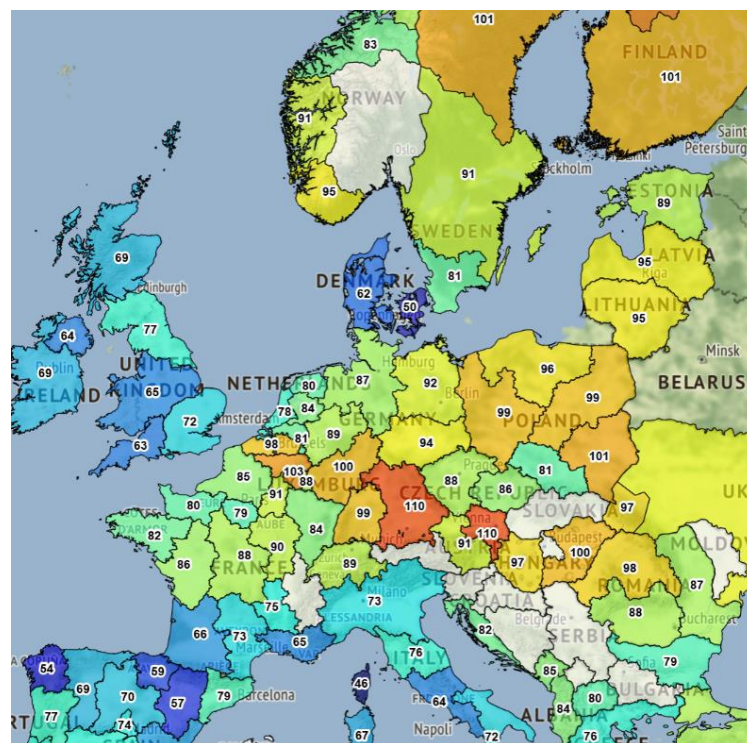


the most: this means that many WPPs did not have hub height data, but had the turbine type with a rotor diameter specified, which was used in estimating the hub height in (1).

A pan-European view of the resulting average onshore wind hub heights is shown in Figure 7, with distinct differences between the regions. E.g., in Germany the highest hub heights are found in the south where wind speeds are on average lower. For Denmark, UK, Spain and Italy, average hub heights are generally lower; for Nordic countries, with relatively new installations, hub heights are generally quite high.



**Figure 6.** Shares of WPP hub heights that were estimated using the four different stages (as shown in Figure 3), as percentages of installed onshore wind capacity.



**Figure 7.** Estimated weighted (by installed capacity) average onshore wind hub heights in meters representing installations at the beginning of 2015. Regions with less than 10 MW of installed wind power are left blank.

#### 4. Effects on future capacity factors in simulations

This section shows how the modelling of today's hub heights is utilized in estimating CF development in a future scenario for two example countries, namely Denmark and Finland. The resulting onshore wind CFs are compared, and the importance of estimating the missing hub height data is discussed.



#### 4.1. Scenario assumptions

To analyse the expected development of CFs in the future, a scenario until 2050 was created. It is assumed that onshore hub heights increase towards an average of 120 m by 2050, and specific power decreases so that by 2050 it is on average 30 % lower than today. Results for Denmark (DK) and Finland (FI) for onshore wind are shown in Table 2. Average onshore wind hub height in Finland raises to 120 m already by 2030, but is not assumed to increase further. In Denmark, the increase of the average onshore wind hub height is assumed to take longer, consisting of both new installations and repowering.

#### 4.2. Comparing capacity factor development

The onshore wind CFs for today (installations at the beginning of 2015) for Denmark and Finland are shown in Table 2. It can be seen that the today's CF for Finland is slightly higher than for Denmark, although Denmark is considered windier than Finland. This difference is explained by the newer WPP fleet in Finland, resulting in a high weighted average hub height for today (104 m), as seen in Table 2. In scenario year 2030 the two countries have quite similar CFs, but by 2050 the CF of Denmark is much higher than that of Finland.

**Table 2.** Onshore wind hub height and capacity factor developments in the modelled scenario

	DK hub height (m)	DK CF	FI hub height (m)	FI CF
<b>Today (2015)</b>	60	0.24	104	0.25
<b>2030</b>	87	0.34	120	0.33
<b>2040</b>	103	0.39	120	0.35
<b>2050</b>	120	0.45	120	0.37

Hub heights are averages weighted by installed capacities. CFs are averages of 35 simulated meteorological years. Calibration of today is based on data from [11] for Denmark, and [12], [13] for Finland.

#### 4.3. Issues if missing hub heights are not estimated

Finland shows a weighted average hub height of 104 m for today (Table 2), which explains the CF being higher in Finland than in Denmark; however, without estimating the missing hub heights, the weighted average would have been only 62 m for Finland (as many newer installations had missing data). Thus, missing hub height estimation was crucial in understanding the today's CFs in the two countries.

It is important to also consider the effect of scaling, as explained in Section 2.3. If the incorrect average hub height of 62 m would have been used for Finland for the today's scenario, the CF of 0.25 shown in Table 2 would still have been met: by scaling wind speeds from the assumed height of 62 m up significantly (because scaling can always meet any CF target). As scaling is assumed to stay the same in the future scenario, the incorrect scaling would have been used in the scenario up to 2050; this would have created an incorrect CF development for Finland towards 2050. This amplifies the importance of modelling the current installations in detail when applying the reanalysis wind speed scaling.

#### 4.4. Modelling forest regions

Finland and Denmark are quite different countries in terms of forest areas, and this needs to be taken into account in the modelling to draw reliable conclusions on the differences between the countries. In the modelling presented in this paper, this has been carried out in two ways. Firstly, forest regions are considered in the WRF modelling. Even though in the WRF modeling at 10 km x 10 km spatial grid spacing it is not possible to explicitly resolve the effect of most forest regions in the Nordic countries, the surface roughness length of grid boxes with forest as dominant land type has been increased to 0.9 m, following the recommendation of [14]. Secondly, the calibration of wind speeds to meet historical wind

power generation, as explained in section 2.3, is used to take into account local environment that may not be fully modelled in WRF.

## 5. Conclusion

In this paper, a methodology for estimating missing hub height data was developed. Regression modelling using large WPP and turbine datasets were utilised to estimate a hub height for each analysed WPP. The resulting hub heights show interesting differences on European level. The different expected future CF developments for two countries with different existing WPP fleets, namely Denmark and Finland, were presented. The importance of estimating the missing hub heights when applying the scaling of reanalysis wind speeds was demonstrated. The modelling can be applied on a pan-European level, as required, e.g., in the simulations for the PECD database.

## 6. Acknowledgements

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